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Magnetic field effects on emission spectra at Z-relevant conditions

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Outline

- **Zeeman splitting in simple K-shell ions**
  - theoretical basis
  - model implementation & comparisons
  - scaling of various broadening mechanisms at Z conditions
  - spectral regions with diagnostic potential

- **Magnetic field effects in L-shell ions**
  - strength transfer to forbidden line… probably not useful on Z

Zeeman splitting: theoretical basis

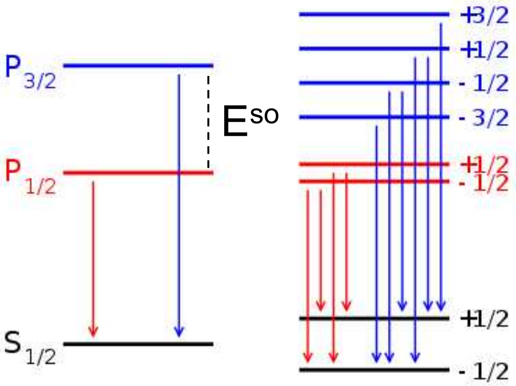
Recall that atoms create their own internal magnetic fields

- electrons moving in the electric field of the nucleus generate B ~ v x E;
  this leads to spin-orbit splitting of *nlj* orbitals into fine structure terms $^{2S+1}L_J$
  E^{so}(2p) ~ 1 eV for neon and ~ 80eV for krypton

"Weak" external magnetic fields: $\mu B \ll E^{so}$ (μ = 5.8e-5 eV/T)

- destroy degeneracy of magnetic sublevels, which are shifted in energy by $\mu B g_J m$
  Lande factors g_J are dependent on the fine structure terms and line intensities are proportional to squares of 3-j coefficients

weak-field Zeeman splitting in hydrogenlike ions (from Wikipedia)



"Strong" external magnetic fields: $\mu B \gg E^{so}$ (Paschen-Back)

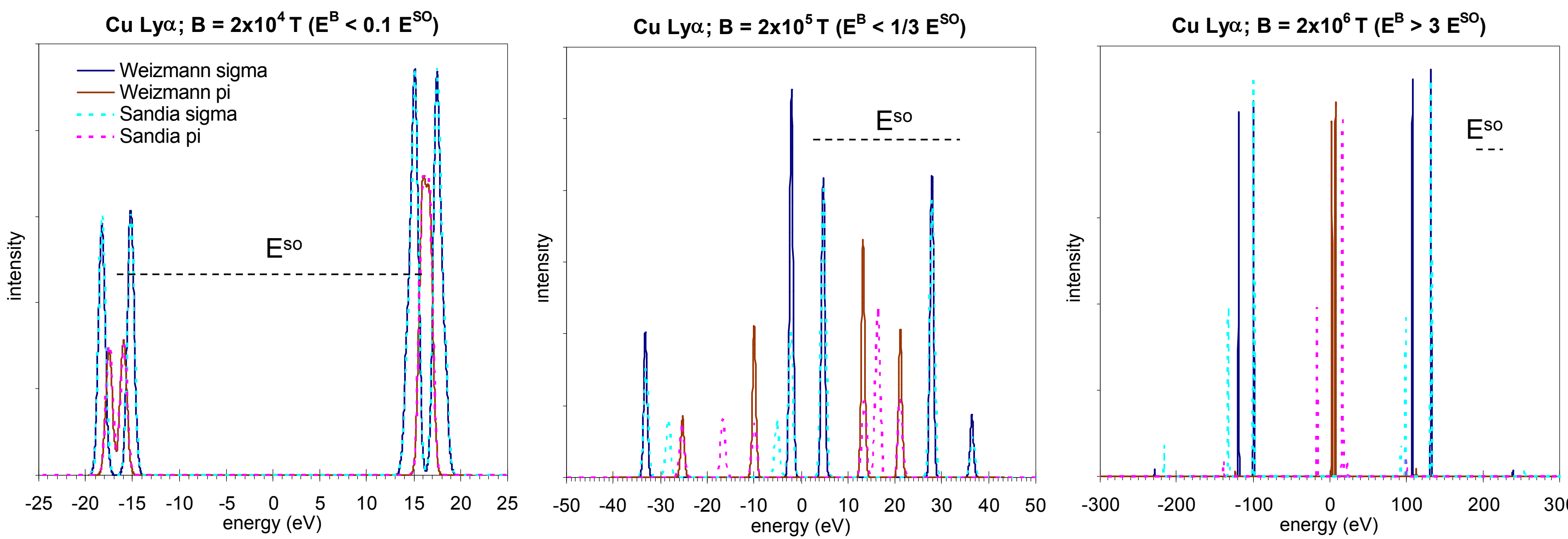
- External field overwhelms internal splitting, giving rise to a simple triplet of lines with equal intensities at shifts of $\mu B \Delta m$; Δm = {-1, 0, +1}

Model approach: add splitting to SCRAM

Weak-field splitting and intensity distributions are determined for pure LS coupling

At intermediate field strengths, comparisons with *ab initio* Weizmann Institute calculations are used to correct perturbative energy shifts

High-field limit is enforced through linear interpolation on $\chi = E^{SO}/(E^{SO}+\mu B)$



Comparisons performed for Ar & Cu He- and H-like ions at various field strengths.
Good match of polarization, line-of sight effects (π is $\Delta m=0$, σ is $\Delta m = +/-1$), and total splitting.
High-energy wings will be most reliable; internal intensity modulations may be unreliable.

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Weizmann method: take advantage of differential splitting

Since Lyα2 is broadens more than Lyα1 but has identical Stark, temperature, motional, and opacity broadening, the difference between the two widths isolates the effect of B field.

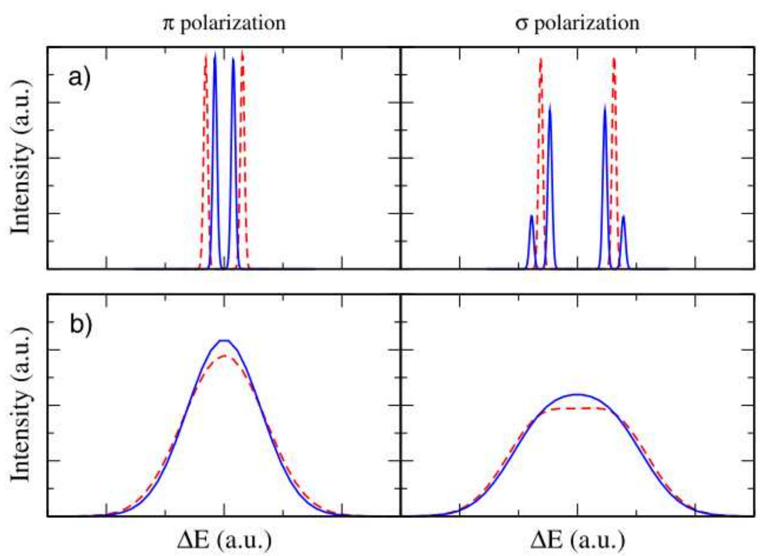

FIG. 1 (color online). Zeeman splitting of the $^2S_{1/2}$-$^2P_{3/2}$ (solid curves) and the $^2S_{1/2}$-$^2P_{1/2}$ (dashed curves) components of a ^2S-^2P transition, convolved with a small (a) and a dominant (b) Doppler effect (that is assumed to be the same for the two components). Profiles of the σ and π polarizations are given separately. For the comparison, the intensity of the $^2S_{1/2}$-$^2P_{1/2}$ component is scaled up by 2 times, to match the intensity of the $^2S_{1/2}$-$^2P_{3/2}$ component.

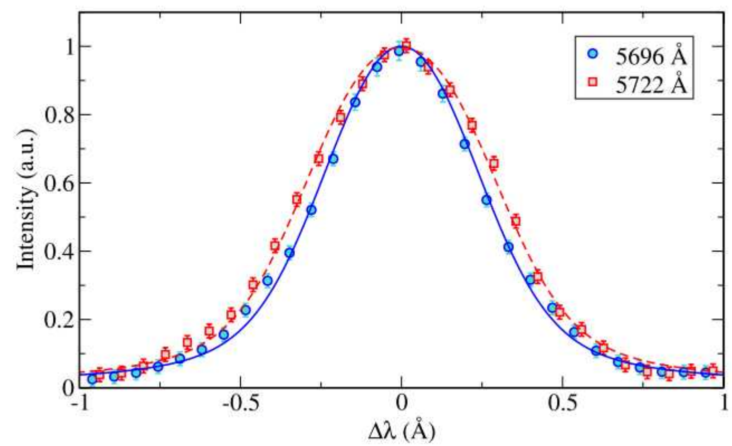

FIG. 5 (color online). The AlIII 4p-4s (5696 & 5722 Å) doublet. The line shapes of the two components are peak-normalized and shifted to a common spectral center. The smooth lines represent best-fit calculations for $B = 0.9$ T, $N_e = 2 \times 10^{16}$ cm^{-3}, and $T_e = 10$ eV.

Stambulchik, Tsigutken, and Maron, *Phys. Rev. Lett*. **98**, 225001 (2007).

Zeeman splitting for magnetic field diagnostics

Relative magnitude of magnetic field splitting vs. other broadening mechanisms:

	Al Lyα	Cu Lyα	Cu Lyβ	
E^{ph} (E^{SO}):	1730 (1.3)	8700 (33)	10300 (10)	
Zeeman: $\Delta E^{z} \sim 2\mu B$ ~	0.04 – 3.5	0.04 – 3.5	0.04 – 3.5	B = 0.3-30kT
instrumental: $\Delta E^{inst} \sim E^{ph}$/resolution ~	0.9	4.4	5.1	res = 2000
thermal: $\Delta E^{th} \sim E^{ph}(T_i/Z_n)^{1/2}/2e4$ ~	1 – 1.3	4 – 7	4.5 – 8	T_i = 1000-3000
motional: $\delta E^{m} \sim E^{ph}(v/c)$ ~	0.5 – 5	3 – 30	3.5 – 35	v = 10-100cm/μs
Stark: $\Delta E^{Stk} \sim 7(40)/Z_n(n_e/10^{22})^{0.58}$ ~	0.04 – 2	0.02 – 1	0.06 – 5	ne = 10^{20}-10^{23}

Even if Zeeman splitting is not dominant, magnetic field information can be obtained by comparing lines that respond differently to B – Weizmann method: Stambulchik, Tsigutken, and Maron, *Phys. Rev. Lett*. **98**, 225001 (2007).

Lyα seems to be the most promising candidate for K-shell B diagnostics:

- Stark broadening is significantly less for α than for β lines
- Satellites of Lyα tend to be better separated than those of Heα
- Simple spin-orbit splitting enables use of Weizmann method for weak fields, eliminating need for independent characterization of ρ, T, opacity, Stark line shape…

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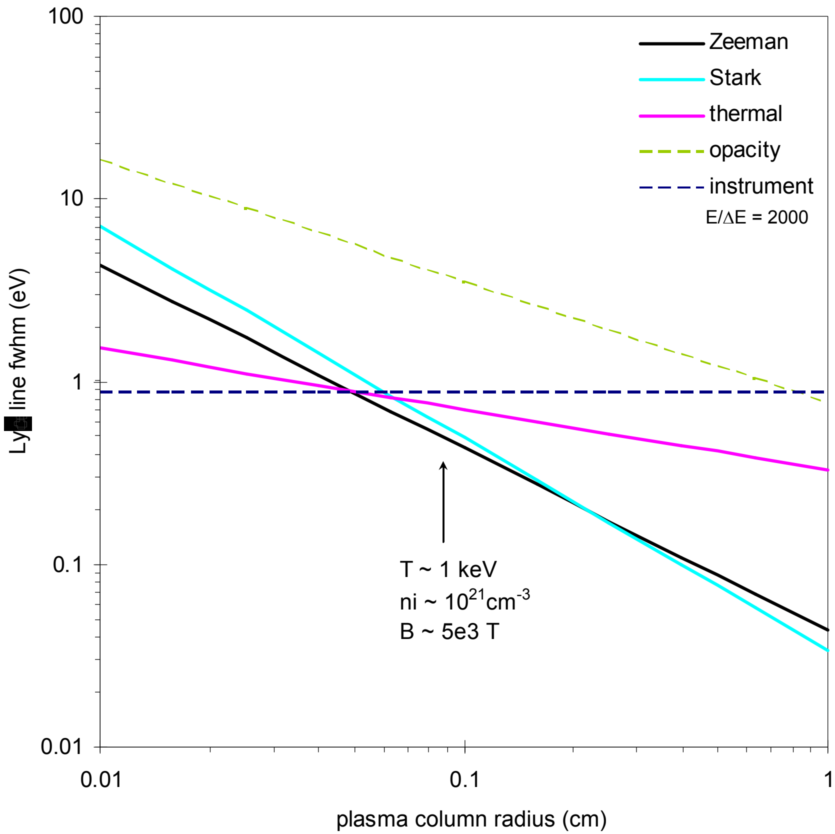
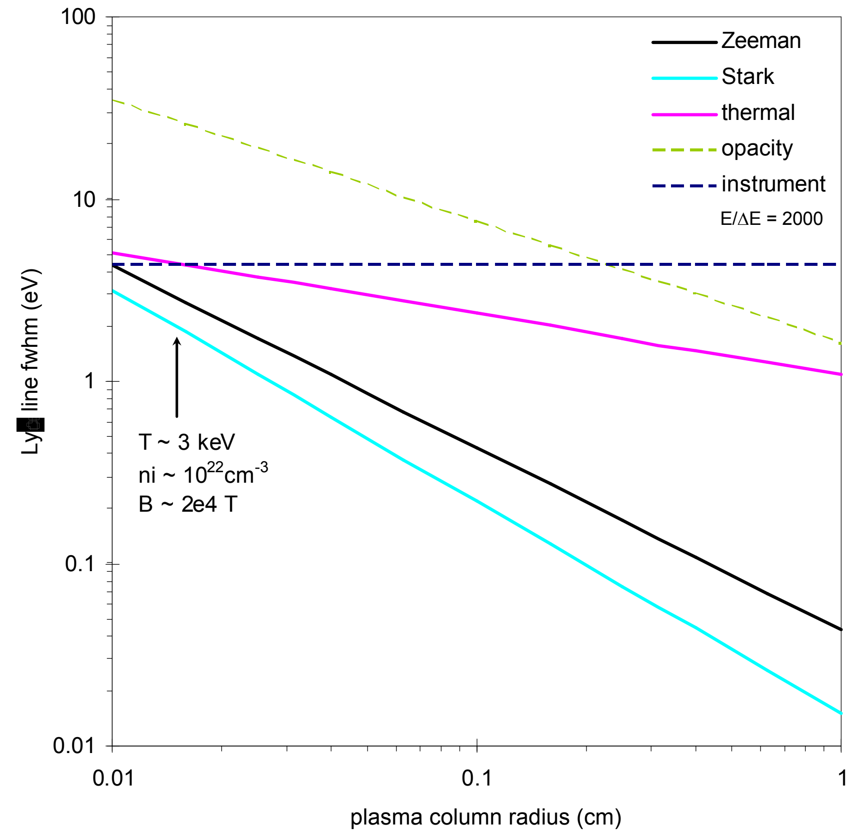
A generic 1 mg/cm pinch illustrates competitive broadening mechanisms in accessible regimes

Plots show Zeeman, Stark, thermal, and opacity broadening of Al and Cu Lyα at a fixed linear density imploded to form a uniform plasma with varied column radius. Temperatures vary as diagnosed for Cu wire array plasma ~3 ns before peak emission.

1 mg/cm aluminum: $E^{Ly\alpha}$ = 1729 eV, E^{so} = 1.3 eV, T = 1

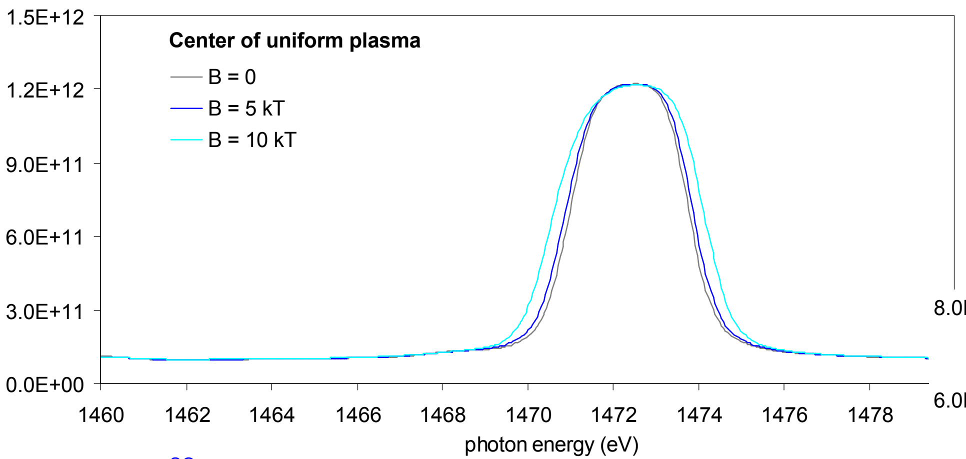


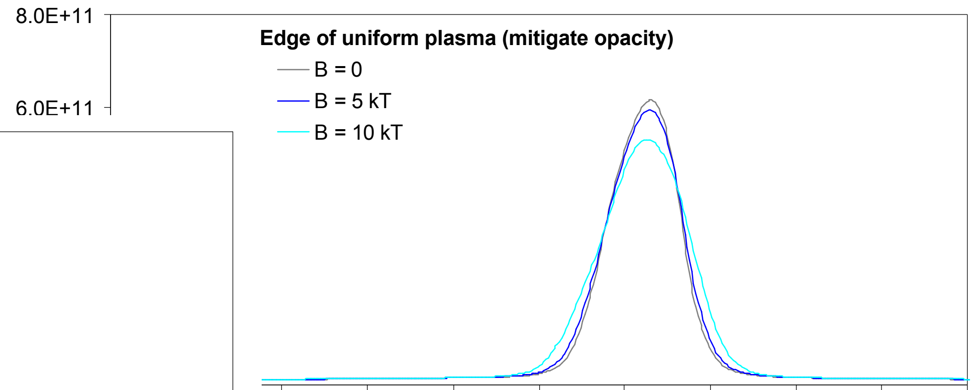
1 mg/cm copper: $E^{Ly\alpha}$ = 8700 eV, E^{so} = 33 eV, T = 3 keV



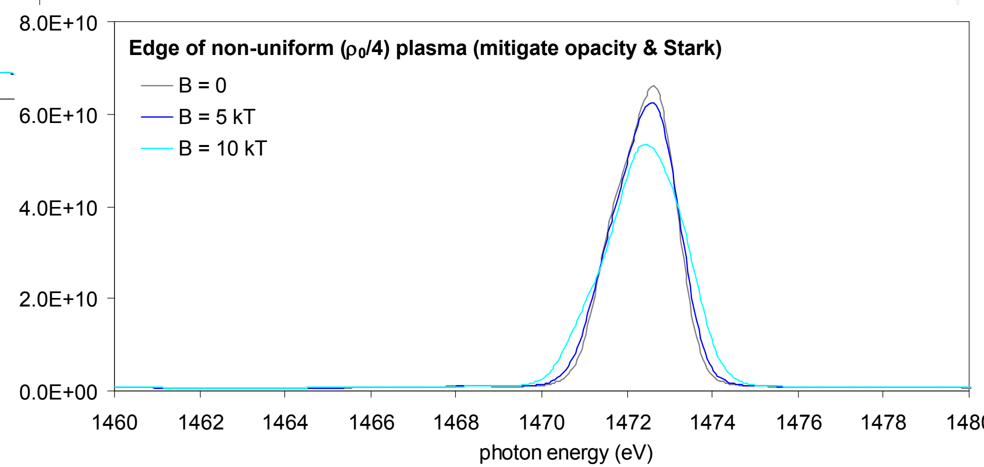
low Z: Mg Lyα B-field diagnostics (2% in Al wire array)

Plasma has T = 1 keV, ne = 1.3×10^{22}/cc, r = 800 μm, ~ 2% Mg (res = 2000)





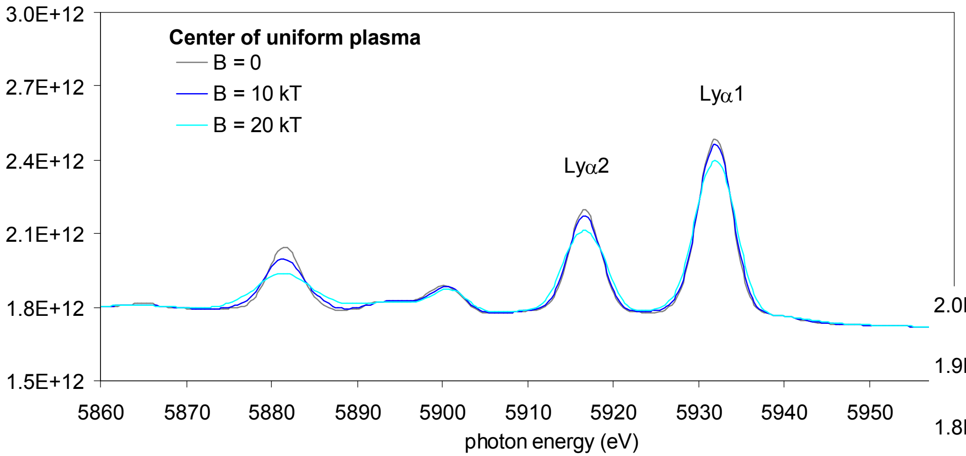
E^{SO} ~ 1.0 eV
ΔE^{z} ~ 0.6 -1.2 eV
ΔE^{inst} ~ 0.7 eV
ΔE^{th} ~ 0.7 eV
ΔE^{Stk} ~ 0.7 eV

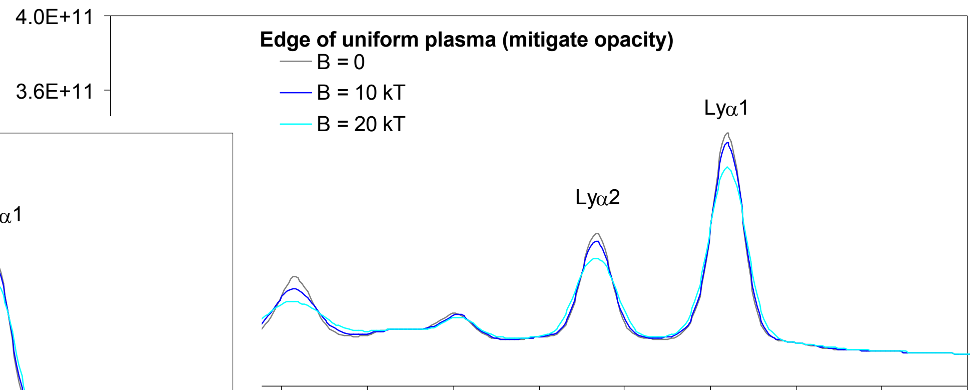


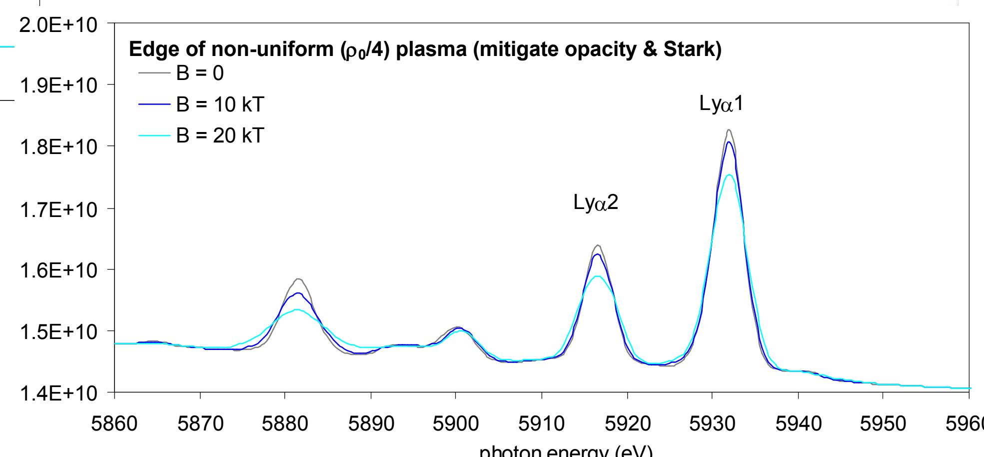
Mg Lyα is barely sensitive to nominal field of B~5 kT and Weizmann method cannot be used -- so Stark, thermal, and opacity broadening all need to be well characterized by diagnostics in a different spectral range (1.8-2.1 keV for Mg Lyγ, Al Heβ, and edge would work).

mid Z: Cr Lyα B-field diagnostics (impurity level in wire array)

Plasma has T = 2 keV, ne = 1.3×10^{22}/cc, r = 300 μm, ~0.1% Cr (res = 3000)







E^{SO} ~ 15 eV
ΔE^{z} ~ 1.2 -2.4 eV
ΔE^{inst} ~ 1.8 eV
ΔE^{th} ~ 2.5 eV
ΔE^{Stk} ~ 1.3 eV

Although other broadening mechanisms compete, Cr Lyα is sensitive to nominal field of B~10 kT. Well-separated satellites provide thermometer and Weizmann method could be used. No other spectral range must be measured and required temperatures are moderate.

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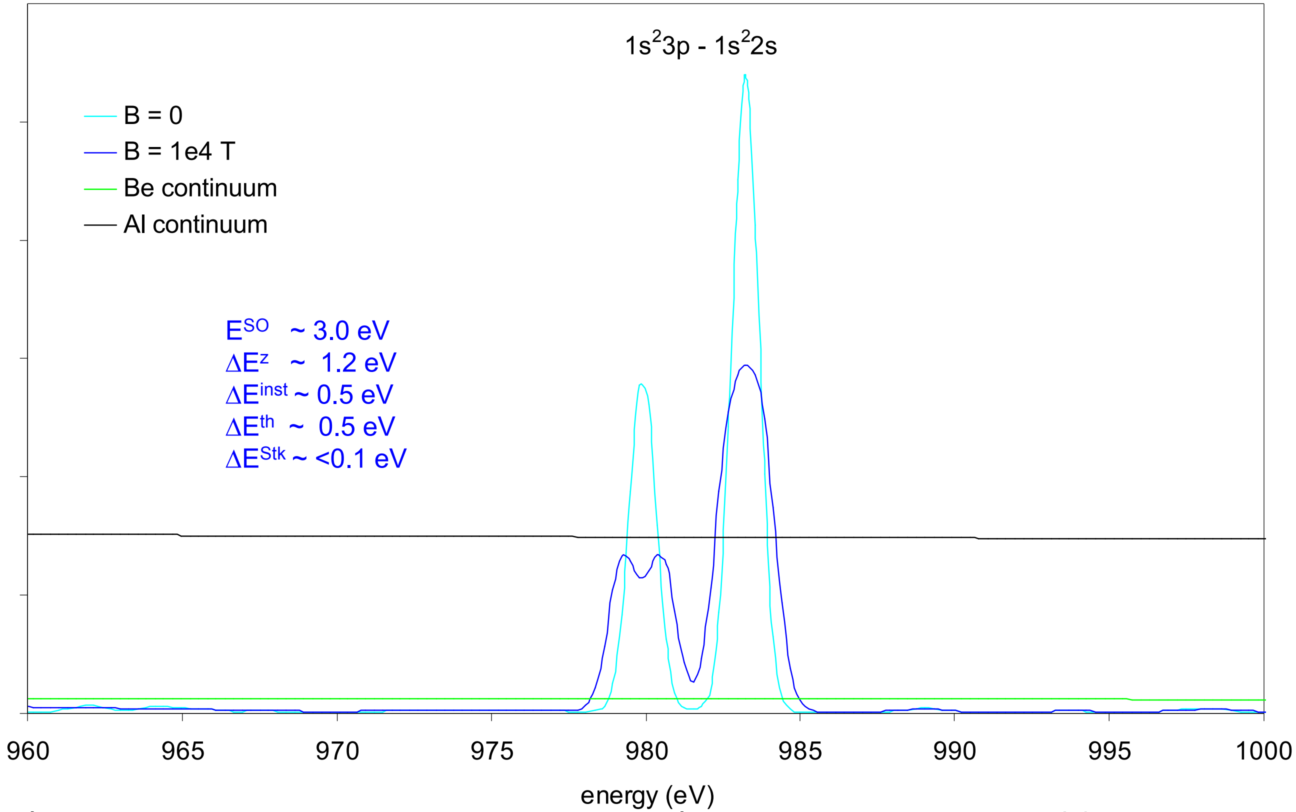
mid Z: Cr Li Lα B-field diagnostics (impurity level in wire array)

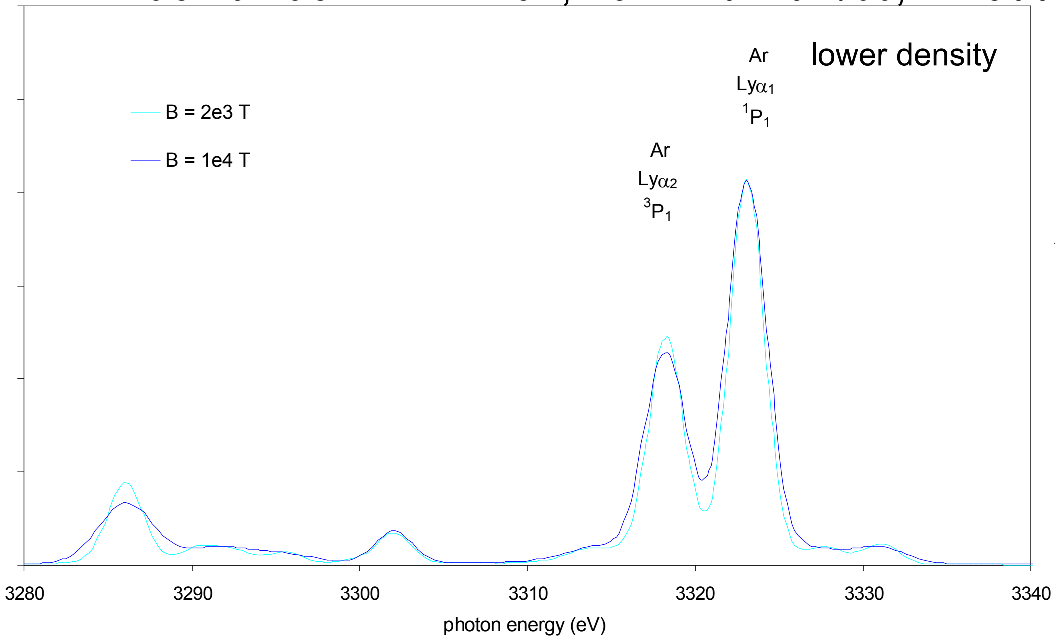
Plasma has T = 2 keV, ne = 10^{20}/cc, r < 1 cm, ~ 0.1% Cr (res = 2000)

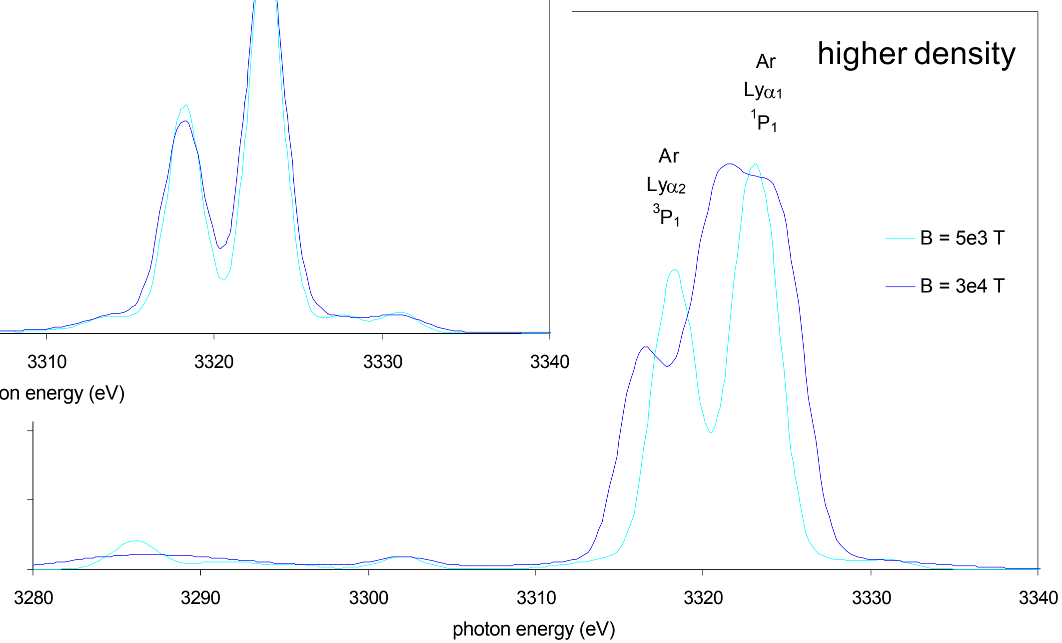


Li-like Cr Lα (a direct analogue to hydrogen-like) is sensitive to B < 10 kT. No satellites; Weizmann method could be used. No other spectral range must be measured and required temperatures are low to moderate. Might be difficult to measure in Al with other impurities.

mid Z: Ar Lyα B-field diagnostics (dopant in gas puff or MagLiF)

Plasma has T = 1-2 keV, ne = 1-6x10^{21}/cc, r = 800-300 μm, < 0.1% Ar





E^{SO} ~ 8 eV
ΔE^{z} ~ 1.2-3.6 eV
ΔE^{inst} ~ 1.1 eV
ΔE^{th} ~ 1.5 eV
ΔE^{Stk} ~ <0.3 eV

Ar Lyα is sensitive to nominal B fields at various stages of implosion. Weizmann method could be used. No other spectral range must be measured and required temperatures are moderate.

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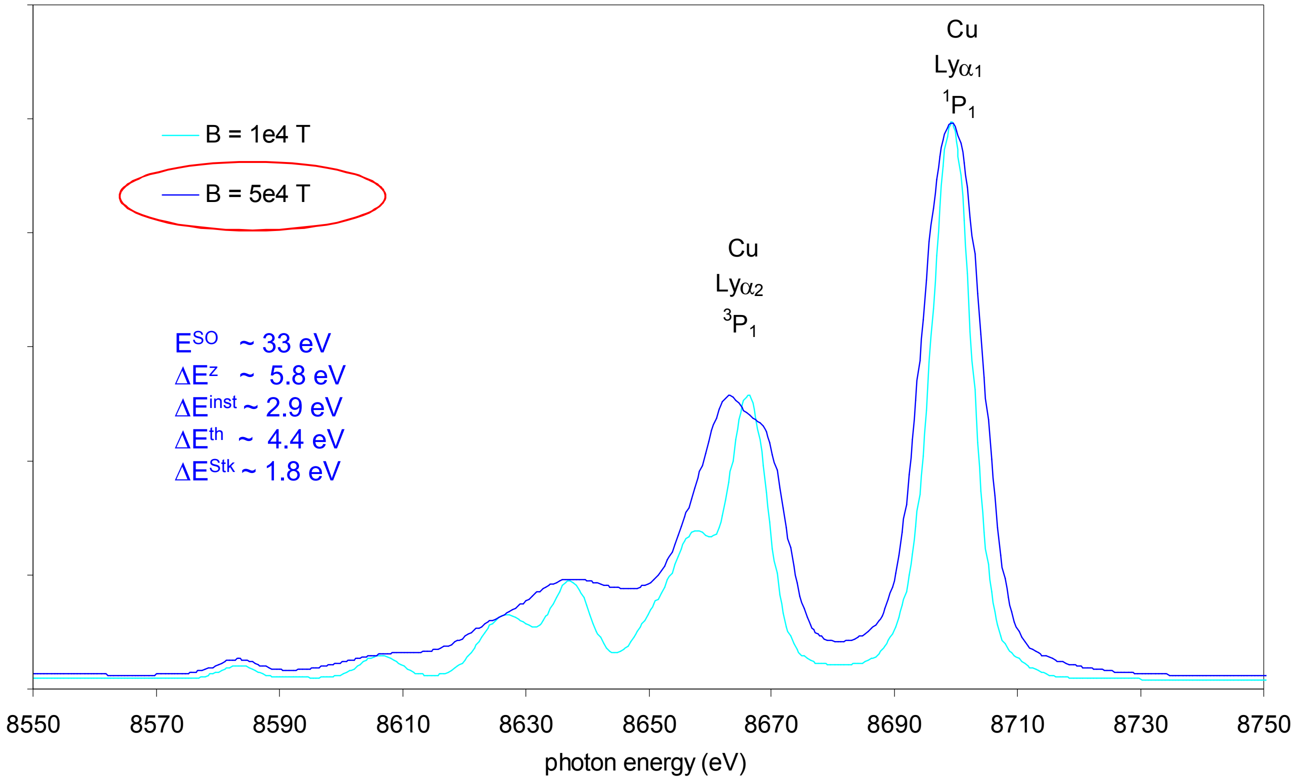
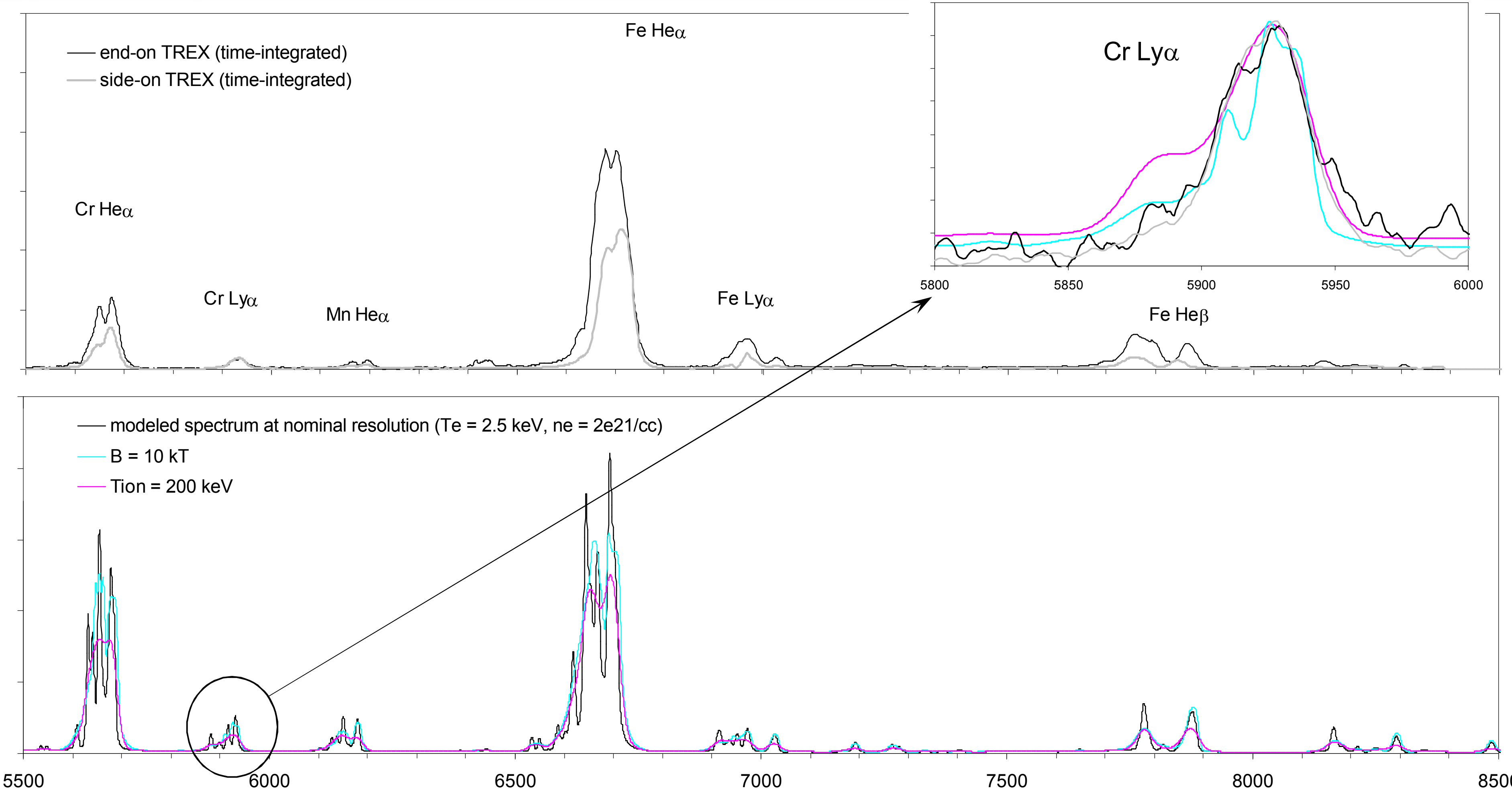
high Z: Cu Lyα B-field diagnostics (impurity level in wire array)

Plasma has T = 3 keV, ne = 3×10^{23}/cc, r = 150 μm, 0.1% Cu



Although thermal broadening dominates, Cu Lyα is sensitive to field of B>30 kT. Satellites provide thermometer and Weizmann method could be used on blue line wings.
No other spectral range must be measured (but high Te is required).

Zeeman splitting can give reasonable global broadening for time-integrated data (off-center lineout from z2120)



This is NOT a careful analysis: opacity, density, temporal broadening, and bulk motion probably all contribute differently than modeled here… but B ~ 10 kT is as reasonable as T_{ion} ~ 200 keV.

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L-shell diagnostics discovered on EBIT* are sensitive to lower fields

B-field causes mixing of these levels, transferring strength from 3F to $\mathcal{B}$

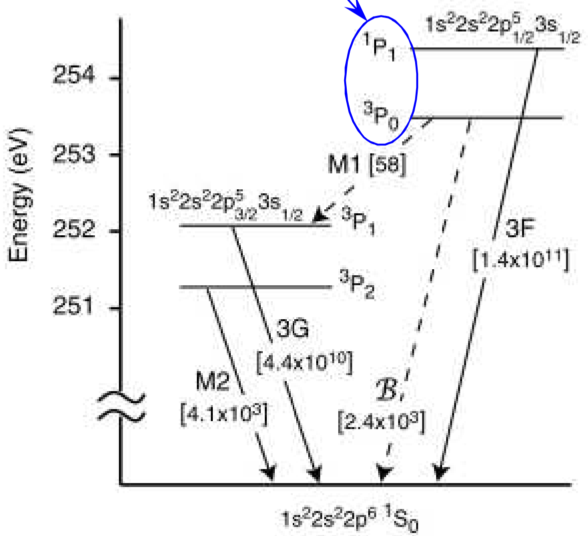
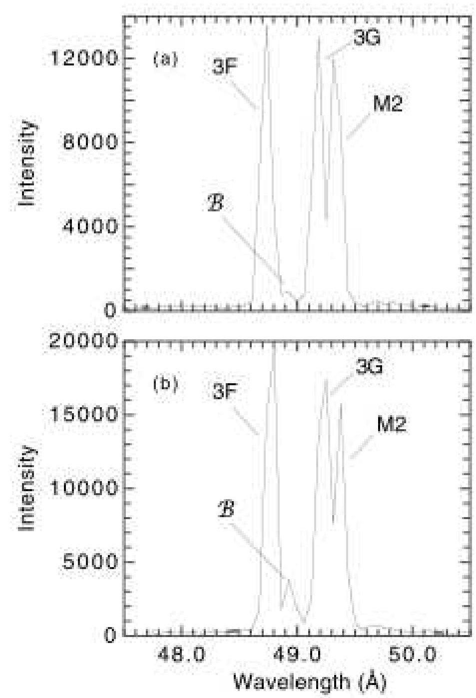


FIG. 1. Grotrian diagram showing the lowest four excited levels in Ar^{8+}. Calculated radiative transition rates (in units of s^{-1}) are indicated in square brackets. The rate for the magnetic field induced line labeled $\mathcal{B}$ assumes a 3-T field.

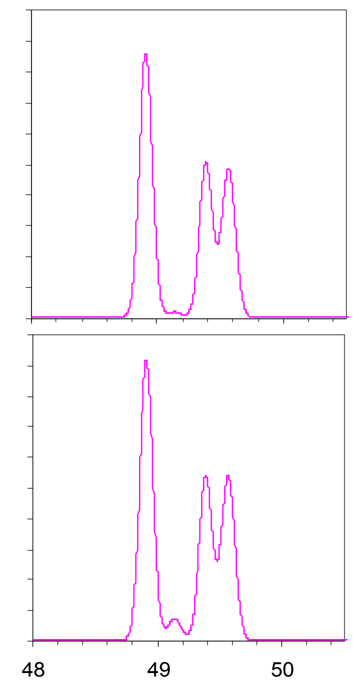
EBIT measurements



Polarized calculations with E^{beam} = 350 eV, n_e = 7x10^{10}/cc

B = 1.1 T

B = 3 T



* Beiersdorfer, Scofield, and Osterheld, Phys. Rev. Lett **90**, 235003 (2003)

Intensity of $\mathcal{B}$ increases as ~ $B^2 / (B^2 + C\, n_e)$;
$\mathcal{B}$ is most sensitive to B fields ~ $(10^{-11}\, n_e)^{1/2}$ Tesla

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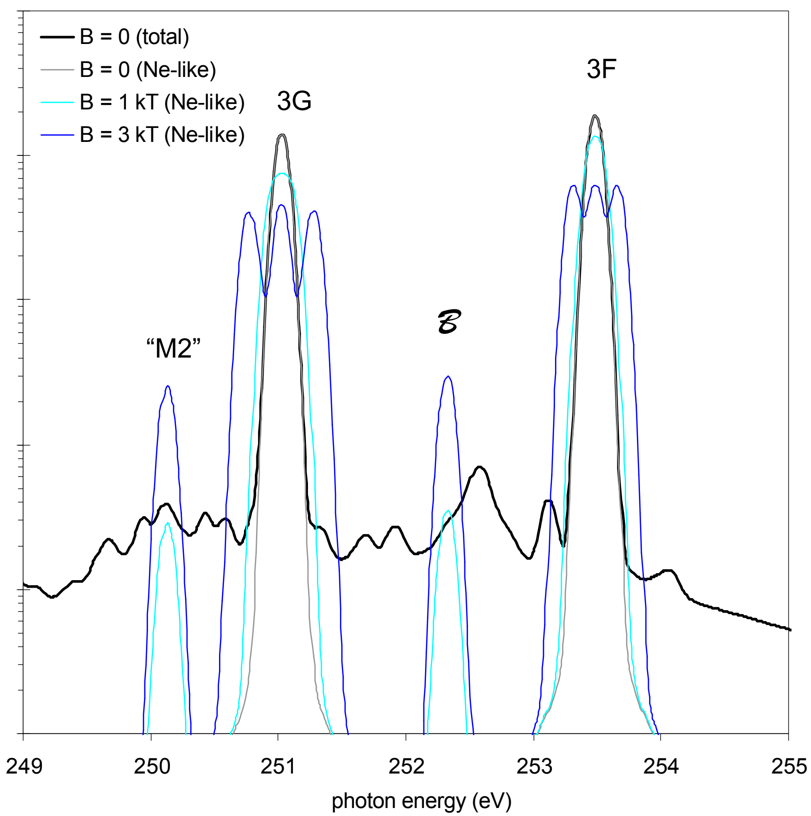
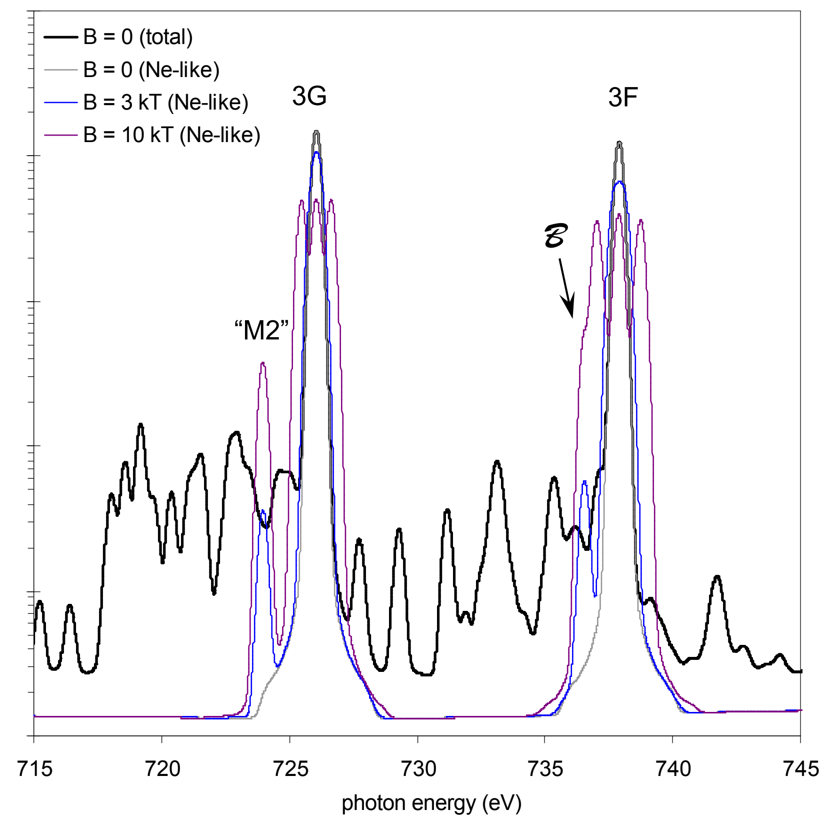
Densities on Z are probably too large for L-shell B diagnostics to work

Argon at n_e = 10^{18}/cc, T = 50 eV (B^{nom}~ 1kT, B^{sens}~ 3kT)



Iron at n_e = 10^{20}/cc, T = 250 eV (B^{nom}~ 2kT, B^{sens}~ 30kT)



Ne-like ions only exist at relatively low temperatures → large radii → small B fields.
Low photon energies from the L-shell ions where ℬ is distinguishable from 3F (Z < 26 → hν < 1 keV) may be difficult to measure, and satellites may complicate marginal cases.

Note: calculations use weak-field coupling to estimate strength transfer

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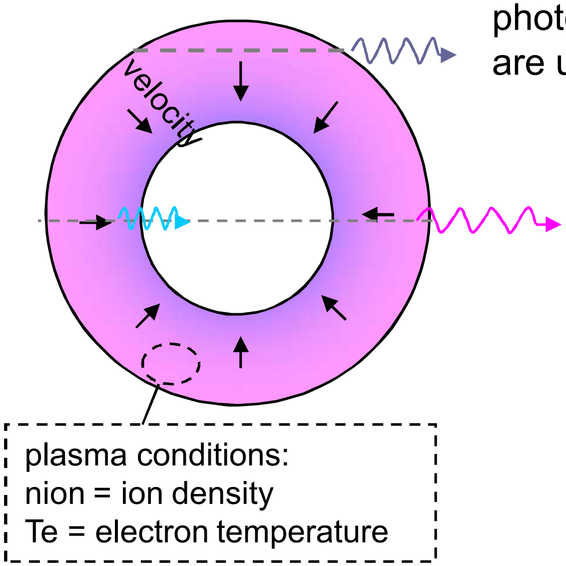
Summary

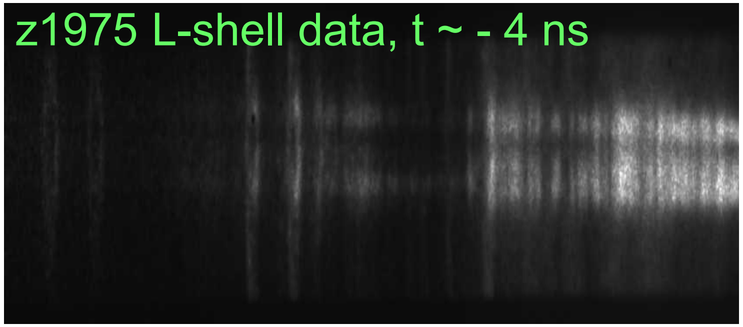
- **Zeemam splitting in simple ions**
  - We have the modeling tools we need:
    - Simple estimates of various broadening mechanisms
    - In-house computational capability for rough lineshapes including all motional & opacity effects as well as Zeeman, thermal, instrumental, & density broadening
    - Collaborations developing for detailed line shape calculations
  - Care must be taken to maximize relative magnitude of expected B-field broadening (axial LOS or radial resolution; low density, low opacity by using dopant/impurity)
  - Weizmann method applicable for mid-Z elements elegantly isolate B-field effects even when they are far from the dominant broadening mechanism
  - Let's propose candidate plasmas and instruments
    - Al 7075/5052 (~0.1% Cr/Ti) wire array (dedicated side-on instrument)?
    - ~0.2% Ar dopant in gas fill (high-res GRAPHIC configuration?)
    - how difficult is high-res for < 1 keV photons (minimize instrumental and thermal broadening) and can we preserve low opacity while retaining signal (impurity in Be)?

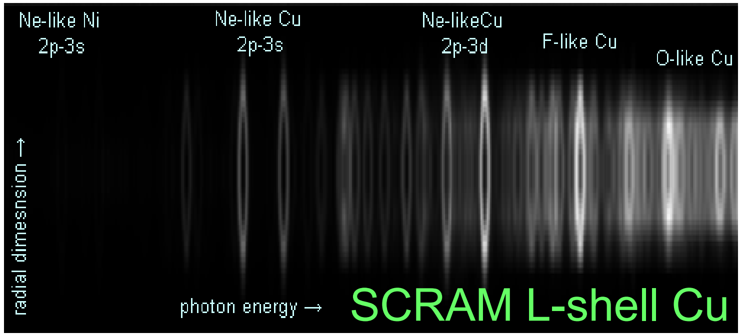
- **Magnetic field effects in L-shell ions**
  - unlikely to be useful as a diagnostic (but it's worth checking for emission 1-2 eV below 3F line that can't be explained by satellites on L-shell spectra we'd measure anyway)

Temporally and spatially resolved spectra give information beyond temperature and density

Imploding Cu plasma shell





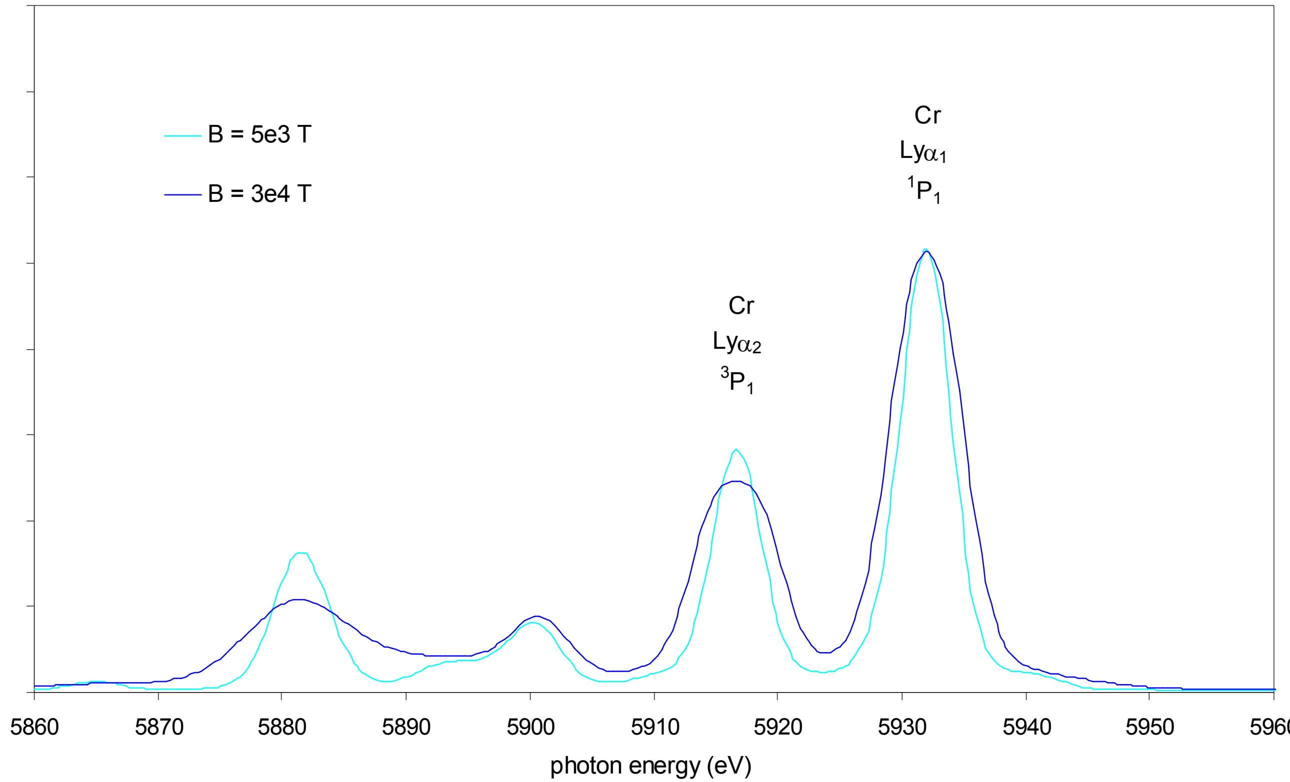


60 cm/μs, T_e ~ 3 keV, n_e ~10^{21}cm^{-3} decreasing over ~ 5mm

Radially resolved spectra from an imploding plasma yield information about implosion velocities and gradients

mid Z: Cr Lyα B-field diagnostics (impurity level in wire array)

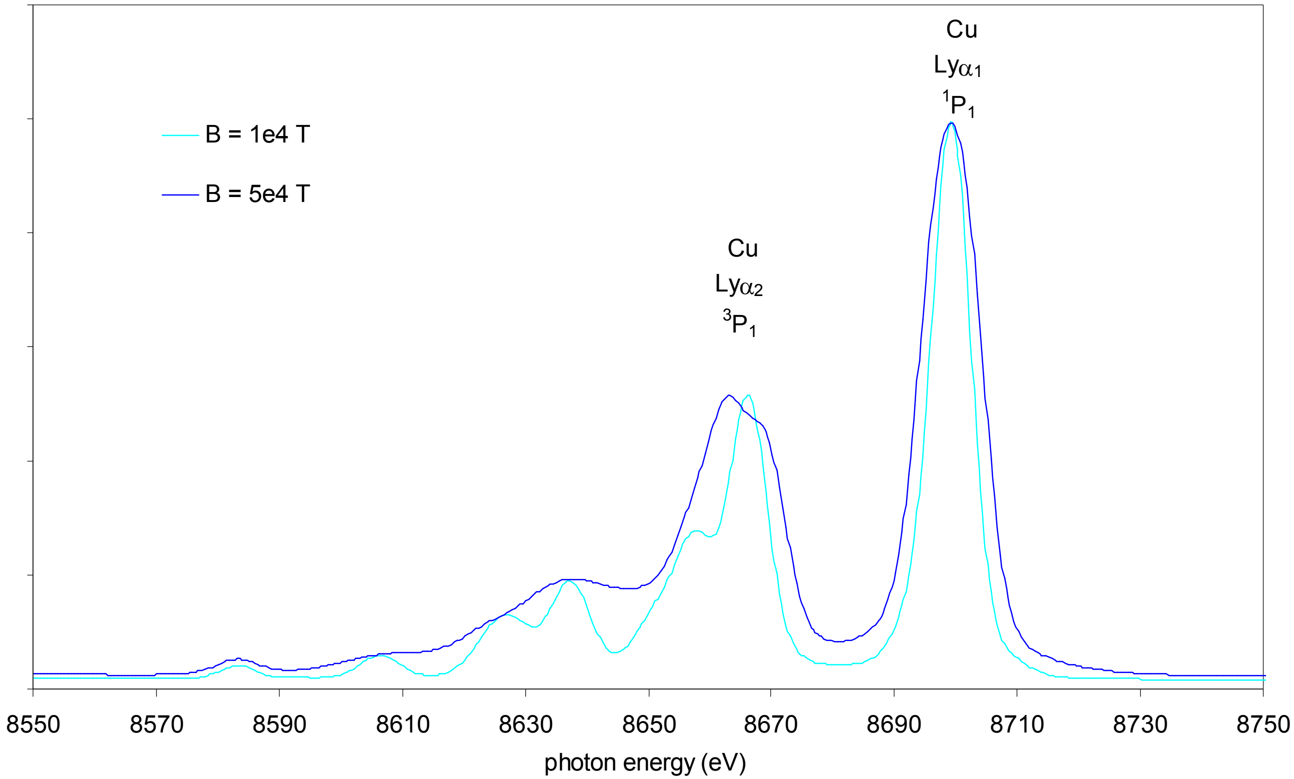
Plasma has T = 2 keV, ne = 9×10^{22}/cc, r = 300 μm, < 0.5% Cr



Although other broadening mechanisms compete, Cr Lyα is sensitive to nominal field of B~10 kT. Well-separated satellites provide thermometer and Weizmann method could be used. No other spectral range must be measured and required temperatures are moderate.

high Z: Cu Lyα B-field diagnostics (impurity level in wire array)

Plasma has T = 3 keV, ne = 3×10^{23}/cc, r = 150 μm, 0.1% Cu



Although thermal broadening dominates, Cu Lyα is sensitive to nominal field of B~20 kT. Satellites provide thermometer and Weizmann method could be used on blue line wings. No other spectral range must be measured (but high Te is required).